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Measuring Runoff and Sediment Production from Forest Roads

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Abstract:

Forest Roads provide access for people to study, enjoy, contemplate, or extract resources from natural and modified ecosystems. Nevertheless, forest roads are an important factor of disturbance, produce runoff and water erosion in the forest areas. The objective of this

study was assessment the impact of four different parts: 1-up hill natural forest, 2- Soil cutslope, 3- Rock fragment cutslope and 4- roadbed, on runoff and soil loss in Patom district in Kheyrud forest research station in northern Iran. Runoff and sediment delivered from four three meter (3×1 m^2) square plots measured in 1-liter bottles per 10 minutes periods in four rainfall events. Our results showed that the steady-state runoff coefficient was 81.6%. The highest soil loss rate was found on the Soil cutslope (191.02 g/m^2), mainly due to low plant cover, and low rock fragments. The total soil erosion on the Soil cutslope was 13 and 270 times higher than those from the roadbed and the natural forest, respectively. The results can help forest managers to know that cutslopes can be considered the main source of sediments on the forest roads and to employ suitable methods to reduce sediment production.

Kay Words: Forest road, Runoff, Sediment, ANOVA

1- Introduction:

Natural forests produce about 1.5 billion square meters of wood per year for human (FAO 2010). It supplies water, air, landscape, food and pharmaceuticals, and habitat for many animals. In order to utilization of these forests and using modern forestry practices, forest roads are an important tool for managing these forests (Abdi et al. 2012). Forest roads have become vital components of the human use of forested systems. Without roads, developing the economic activity critical to the quality of modern life would have been difficult, and roads remain central to many forest uses today (Akay et al. 2008). Roads provide access for people to study, enjoy, contemplate, or extract resources from natural and modified ecosystems. Building and maintaining roads is controversial, however, because of the kinds of uses they enable, concerns about their short- and long-term effects on the environment, and the value that society now places on unroaded wilderness (Cole and Landres 1996, Williams 1998). These roads are considered a form of manipulation and confusion in natural forests. Forest roads deform range, cutting surface and subsurface water flow, reduced vegetation cover, causing soil compaction and erosion and finally cause sediment production in the watershed areas (Tague and Band 2001). Soil erosion is the most significant contributor of off-site ground water pollution on a global scale with most of the contaminants originating within an anthropogenic setting (Marsh and Grossa 1996). Forest road sediment production causing erosion and soil loss, which creates maintenance and repair costs are causing pollution of water resources in forest streams and negative effects on breathing and generation aquatics and finally accumulation behind the dams and reduce its effective life (USDA 2000, Akay et al. 2008, Khalilpoor et al. 2010).

Erosion and sediment production on forest roads depends on many factors such as: hill slope(Packer 1967), road slope (Burroughs and King 1989), trenches slope(Luce and Black 1999), the amount, age and types of roads (Reid and Dunne 1984), distance between the road drainages(Packer 1967), the physical properties of road surfaces (Burrough and King 1989), the amount and intensity of precipitation (Megahan et al. 1991), cutslopes vegetation cover (Lopez et al. 2008), weight and type of vehicle traffic on the road surface (Foltz et al. 2009). Assessment of road contributions to sediment budgets generally relies on a summation of sediment production of each road segment multiplied by the fraction delivered to the stream (Cline et al. 1984, U.S. Department of Agriculture (USDA) Forest Service Northern Region 1997, Dube´ et al. 1998). Thus knowledge about impact of factors is listed in the production and sediment delivered, can be as a useful tool in forest road design to minimize road damage and negative effects of environmental pollution and water resources.

Three methods are typically used to measure sediment produced from forest roads: 1) Measurement in natural condition with natural precipitation events (e.g. direct measurements from outlet of live streams culverts or using sediment traps) (Lewis 1996, Luce & Black 1999, Sheridan et al. 2006, Meadows 2007, Surfleet 2008); 2) use of a rainfall simulator (López et al. 2008, Foltz et al. 2009); and 3) use of empirical and physical sediment prediction models (Akay et al. 2008, Elliot et al. 2009, Khlilpoor et al. 2010).

Luce and Black (1999) showed that cutslope was the main source of sediment production in forest areas. La Marche and Lettenmaeir (2001) said that forest roads have a more persistent impact on hillslope hydrology that other types of disturbances due, in part, to persisting reduced infiltration rates on the compacted surface. Ziegler et al (2001) showed that roads are potentially susceptible to hydraulic erosion processes, and may contribute substantially to streams sedimentation, even during low-magnitude rainfall events. Jordán and Martínez-Zavala (2007) studied about soil loss and runoff rates on unpaved forest roads on three road segments (fillslope, roadbed and cutslope) in southern Spain. Their result showed that the highest runoff coefficient and soil loss was found on the cutslope due to slopes, the existence of loose colluviums, and a low plant cover. Their findings show that the total soil loss from the cutslope was 5 and 6 times higher than those from the roadbed and fillslope, respectively. López et al (2008) in a Mediterranean area also showed that cutslope had the highest runoff coefficient and soil loss rate in forest roads due to low plant cover, soil texture and rock fragments.

As the majority of the forest road templates in mountainous regions of Iran are crowned with a side ditch, soil and rock fragment cutslopes. Given the importance of erosion and sediment production from forest roads, provide knowledge of the road segments potential for erosion, that can help forest managers in Iran, to identify sensitive segments for erosion control operations, When they designing a new forest road network. Therefore, the purposes of this study were to: 1- Assess the effect of forest road toward undisturbed forest on runoff and erosion; and 2- Assess the role of different road segments in sediment production and soil loss.

2- Material and Methods:

2-1 Study site:

The study area was located in the Patom district in the Kheyrud Forest Research Station of Tehran University in northern Iran, which is located at approximately 36 ^{o} 38´ N and 50 ^{o} 34´ E. The Patom district has a 900 ha drainage area and ranges from 0 and 934 masl in elevation. Average annual rainfall is 1300-1500 mm. The mean air temperature is 16.1 ˚C. The average of stand volume is about 55.76 m^3/ha, dominant stand height 25-30 meters, 70% canopy cover and 263 stems/ha. Dominant tree species are *Carpinus betulus* (Hornbeam), *Fagus orientalis* (Oriental Beech) and *Parrotia persica* (Persian Ironwood).The lithological substrate is mainly calcareous parent material and the associated soil types are Inceptisols and Alfisols (Sarmadian et al. 2001). The length of the road network in the district is 16.3 km, with an average density of 18.1 $m.ha^{-1}$. Unpaved forest roads ascending from 620 m to 650 masl were selected for this experiment. This road is used by wood utilization vehicles such as tracks and skidders and other passenger cars such as jeeps and touring cars (Fig 1).

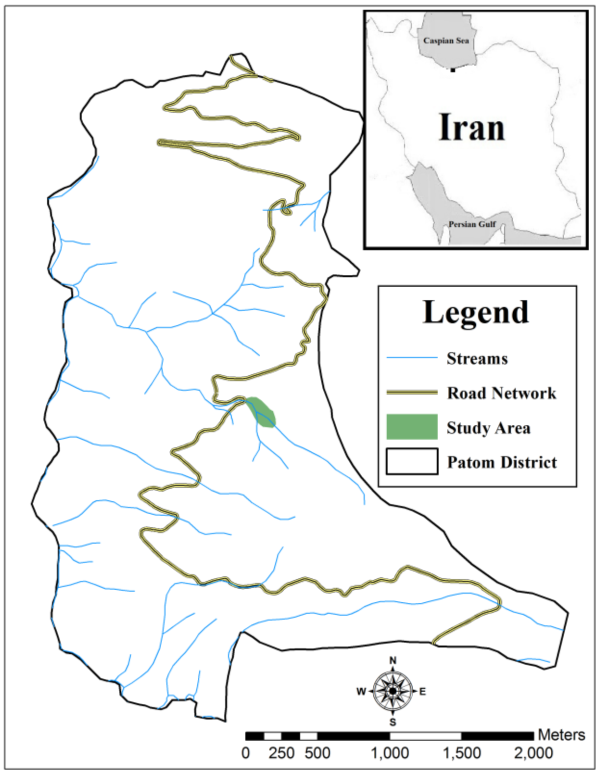

Figure 1: Potom district and study area in northern Iran

One road segment with two different cutslopes selected. Two selected cutslopes were similar in averages, with 30% gradient, 3 m slope length, and about 10% vegetation cover, but they were different in material. One cutslope had exposed more than 70% of soil (named 'Soil Cutslope'), and the other had exposed more than 70% rock fragment cover (named 'Rock Cutslope'). Vegetation cover and rock fragment cover were determined using a 50 cm × 50 cm grid with cells of 0.25 cm^2 (Jordán and Martínez-Zavala 2007). The

slope angle of the soil surface on each cutslope was determined using a clinometer. Four three-meter square (3*1 m^2) bordered plots were located randomly and installed using sheet metal borders with a runoff apron on the uphill forest, two cutslopes and roadbed surface at the bottom of road length slope. The plots were named 'Fpolt', 'Rplot', 'Splot' and 'Bplot' as they were located on the uphill natural forest, Rock Cutslope, Soil Cutslope and roadbeds, respectively. Four rainfall events in moderate intensity [rainfall intensity was between 2.5 to 7.5 mm/h (Mahdavi 2005)] were measured with a cylindrical manual rain gauge, and sediment suspended concentration samples were collected in 1-liter sampler bottles at every 10 min intervals plots. Average rainfall intensities were obtained by dividing rainfall height (mm) to rainfall duration (hour). Peak runoff and runoff coefficient (the percentage of rainfall that becomes runoff) were measured during each rainfall event. Percentage plant cover was measured using a grid with cells of 0.5 cm (Arnáez et al. 2004).

Sediment suspended concentration decanting and filtering through a Watman No. 42 paper under suction on a Buchner funnel in the lab (Gordon et al. 2004). Then papers containing sediment weighed after that they placed in a drying oven for 24 hours at about 105 ^{o}C [Malomo et al. 1983].

2-2 Data analysis:

Assumption of normality was tested using the Kolmogorov-Smirnov and Shapiro–Wilk, at 95% confidence level. (McCune 2004, Rodríguez-Pérez et al. 2007). Since most of the variables did satisfy these assumptions, parametric tests were used (ANOVA for multiple independent samples). When ANOVA null hypothesis accepted, post hoc pair wise comparisons (Post Hoc 'Duncan' test) were performed to investigate differences between pairs of means (López et al. 2008).

The relationship between average sediment concentration (g/l) and elapsed time (min) to the road segments was approached using curve estimation analysis.

3-Results:

3-1 Site observation:

The results of curve estimation analysis showed that average of sediment concentration (g/l) and elapsed time (min) to the outlet of plots from the four road segments measured for sediment concentration, followed a quadratic function. Also our findings showed that maximum of sediment concentration (g/l) observed at middle of each rainfall event in 40-60 min interval, and from Splot, Rplot, Bplot and Fplot respectively (Fig.2).

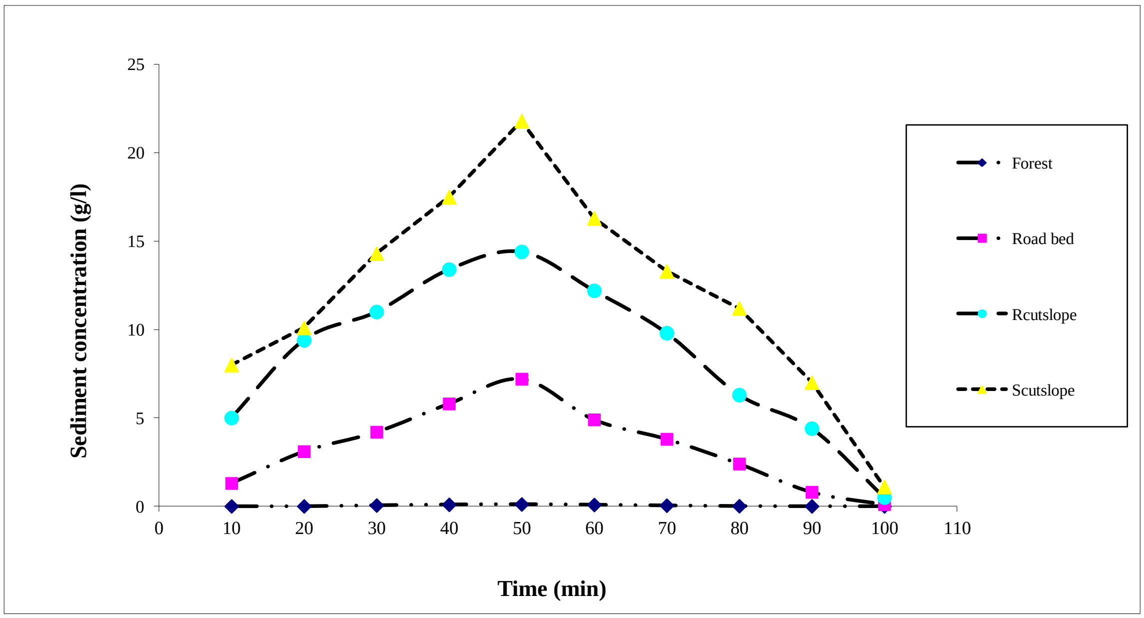

Fig 2. The trend of average of sediment concentration (g/l) observed from each plot during four rainfall events.

Table 1 shows quadratic function fitted by least squares approximation at every plot that describe the sediment concentration (g/l) delivered to outlet of each plot after 10 minutes intervals.

Table 1: Estimated parameters of the quadratic model describing the relationship between sediment concentration (g/l) and elapsed time (min). $Y=aX^2+bX+c$

	Parameter	*Estimate*	*p*	*R*
Fplot	a	-5E-0.5	0.031	0.71
	b	0.05		
Bplot	a	-0.03	0.001	0.87

	b	0.25		
Rplot	a	-0.05	0.000	0.95
	b	0.48		
Splot	a	-0.07	0.000	0.92
	b	0.68		

Results showed that plant cover was the highest on the Fplot (85-95%), on the Splot and Rplot were the same (≥15%) and it wasn't any plant cover on the Bplot (0%).

3-2 Analytical analysis:

The normality tests (Kolmogorov-Smirnov and Shapiro–Wilk) showed that the accuracy data were normality distributed ($P \geq 0.05$). ANOVA analysis showed significant differences in runoff peak (ml/s) and runoff coefficient (%) between the four Plots of the road ($p \leq 0.001$). The highest mean steady-state runoff coefficient was determined for the Splot (81.6%), also steady-state runoff coefficients for the Rplot, Bplot and the Fplot were 77.8%, 75.8% and 10.2% respectively (Table 2).

Table 2: Hydrological results from four rainfall events

Plots	*Fplot*	*Bplot*	*Rplot*	*Splot*	*ANOVA,p*

Surface Runoff (ml/s)					
Mean	0.2^{a}	1.4^{b}	1.5^{b}	1.8^{c}	0.000
±SD	0.03	0.15	0.14	0.2	
Peak Runoff (ml/s)					
Mean	0.4^{a}	1.9^{b}	1.7^{b}	2.5^{c}	0.000
±SD	0.08	0.18	0.18	0.16	
Runoff coefficient %					
Mean	10.2^{a}	75.8^{b}	77.8^{b}	81.6^{c}	0.000
±SD	2.5	17.3	15.6	23.2	

Also ANOVA analysis showed significant differences in sediment concentration (g/l) and soil loss (g/cm^2) between the four Plots of the road ($p \leq 0.001$), specifically the mean sediment concentration (g/l) was the highest at the Splot after that Rplot, Bplot and Fplot were higher respectively. The highest values of soil loss observed on Splot (191.02 g/cm^2) (Table 3).

Table 3: Average of sediment concentration (g/l) and soil loss (g/m^2) from four rainfall events

Plots	*Fplot*	*Bplot*	*Rplot*	*Splot*	*ANOVA,p*
Sediment concentration (g/l)					
Mean	0.03^{a}	3.36^{b}	8.64^{c}	12.06^{c}	0.001
±SD	0.04	2.27	4.45	5.92	

Total soil loss (g/m^2)					
Mean	0.71[a]	13.65[b]	152.10[c]	191.02[d]	0.000
±SD	0.26	1.91	9.25	4.36	

4-Discussion:

Unpaved forest roads in mountain areas modify the hydrological functioning of hillslopes, and they can make an important contribution to the sediment budget of many forested basins (Arnáez et al. 2004). Unpaved roads can increase the hillslope-scale sediment production rates by up to four or six orders of magnitude relative to undisturbed conditions (Ramos-Scharrón and MacDonald, 2007; Croke et al. 1999). Suspended sediment includes the wash load of fine particles such as silts and clays (<0.06 mm) that are washed from banks and hillsides into streams during runoff events, and the bed load materials that are suspended due to turbulence and high flow events (Chang 2003). The evolution of average of sediment concentration (g/l) in runoff is represented in Fig 2. The average of sediment concentration (g/l) increased linearly at the beginning because it took time for the soil to get wet, as well as for the particles to become detached. The average of sediment concentration (g/l) increased during the first 40–50 min of rainfall event. After 50 min from the beginning of the experiment, there was a steady decrease in sediment concentration. Lopez et al (2008) showed that the average of sediment concentration (g/l) and elapsed time (min) to the outlet of plots from the four road segments measured for sediment concentration, followed a quadratic function with a maximum point. This is in agreement with our results (Fig 2 and Table 1).

According to Poesen et al (1994) the influence of surface rock fragments on sediment yield from bare interrill areas largely depends on the effects of rock fragments on sub-surface flow and on sediment concentration. On the cutslope with the rock fragments at the surface increased the roughness and the interception of raindrops, these causes reduce soil detachment and sediment production. Therefore runoff and soil lost from Rplot was lower than Splot. Also Arnaez et al. (2004) and Jordán and Martínez-Zavala (2007) Showed that, cutslopes can be the primary source of sediments on forest roads, but soil loss rates are partly determined by the rock fragments and this factor on the of the cutsloes, had statistically significant effects on runoff and erosion. These results support our finding that rock fragments on cutslope are effective on the sediment production and soil loss (Tables 2&3).

Due to compaction of the soil surface (in study area), roadbeds had lower sediment concentration than cutslopes plots (Tables 1&2). The compacting of roadbed may also explain the low availability of sediments, since splashing is unable to detach the particles. Rills were not formed in the rainfall events because of the small dimensions of the plots. However, vehicle ruts or high intensity storm can promote the development of rills and shallow gullies in the wet season (Arneaz et al. 2004; Fultz et al 2009). Once developed, they behave similarly to ditches in capturing and re-routing surface water and cause most of the erosion (MacDonald et al. 2001). Some authors (Reid and Dunne 1984; Ziegler et al. 2001) suggest that there is a relationship between sediment production and the intensity of forest road use. Our finding is supported by Arneaz et al (2004) and López et al. (2008) that showed sediment produced from roadbed was lower than cutslope. In the other hand,

because of removing vegetation cover over the roadbed it had more runoff and erosion from natural forest (Fig 2 and Tables 2&3).

The Fplot on natural forest show the lowest values of surface runoff (0.2 ml/s) and erosion (0.71 g/m^2) (Tables 1&2). The accumulation of loose material coming from the construction of the road, or from the washing away of the fines mixed in with the roadbed, facilitates infiltration and reduces runoff. The high percentage of vegetal cover also reduces the amount of rain splash erosion. However, runoff and erosion may be more active if the gradient and the stones in the soil increase. A high percentage of gravels cause small concentrations of water in the stone borders where the erosion is concentrated. Ramos-Scharrón and MacDonald (2005) and Elliot et al. (2009) said that in natural forest watersheds, erosion is generally low in the absence of disturbances. The most significant effect of forests on precipitation is canopy interception (Chang 2003) and the trees canopy reduces kinetic energy of rain drops. Ahmadi et al (2009) showed that the ratio of interception was 32.1% of total precipitation in forest in northern Iran. These events that mentioned above cause reduce runoff formation and soil erosion on natural forest surface (Fig 2 and Tables 2&3).

Soil losses from forest roads require reconstruction and maintenance costs, and these encompass the majority of costs in forest management plans (Abdi et al. 2010). Sediment suspended cause forest streams and aquatic habitat pollution. Boyd (1990) observed that sediment suspended concentration higher than 20 g/l in streams cause confusion and disorder in the behavior of aquatic species. Although this study did not measure sediment suspended concentration in forest streams and aquatics habitats, it provides some information for forest managers to consider the roadbed and cutslope surface, and using methods to reduce sediment production and reduce stream pollution. Some authors recommended various techniques to minimize disturbance and sediment production in forest roads, such as leaving undisturbed vegetation in areas large enough to accommodate road drainage (Gray and Megahan, 1981), tree planting, seeding and netting (Megahan, 1974), bioengineering techniques (Abdi et al., 2010) and design of proper road drainage (López et al., 2008).

5- Conclusion:

Forest roads are the main source of sediment production on natural forest in northern Iran. Rock fragment and vegetation cover are two important factors on runoff production and detachment and sediment delivery to forest streams.

Our results demonstrates that majority of the sediments come from the cutslopes in forest roads. Runoff and soil loss rates are also active on bed roads, as a recommendation, increasing the plant cover is necessary for reducing the intensity of runoff generation by forest roads.

Forest roads managements with awareness of this issue can pay more attention to more sensitive sections of forest roads and with road maintenance activities (such as increasing plant cover or rock fragment percentage), cause reduce sediment production and prevent water pollution.

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